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EPOXY MATERIALS IN CONSTRUCTION

A GENERAL GUIDE FOR DESIGN, CONSTRUCTION AND MAINTENANCE PERSONNEL

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ABSTRACT

Ontario Hydro uses a large variety of epoxy-based materials for new construction and for the repair of concrete structures. This report is intended to familiarize those involved in design, construction and maintenance with the general properties, uses and limitations of various epoxy-based materials. It outlines the conditions under which the use of an epoxy would be suitable, and provides a discussion of how epoxy products can be modified for specific applications. Guidance is also provided on the proper application techniques (ie, surface preparation, etc.) for these materials. As well, a comprehensive list of other available and pertinent references, including Ontario Hydro reports, is given.

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To Dr. D. Mills
Director of Research

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1.0 INTRODUCTION

1.1 General

In 1989, a Repair Materials Task Group, which is comprised of representatives from various departments within Ontario Hydro, was formed. The objective of the group is to investigate, evaluate and promote repair materials and methods for maintaining the current function of, or extending the life of Ontario Hydro's concrete structures. This report has been prepared under the auspices of the Task Group.

Over the years, the Concrete Technology Section, Civil Research Department, has developed a good data base of information and experience on epoxy-based materials for use in construction and repair, and this report is a compilation of some of this information. The report is intended to provide a general introduction, for design, construction and maintenance personnel, to these materials. General properties, typical applications and potential limitations of these materials will be discussed. As well, the document provides a practical guide for the proper application (ie, surface preparation, etc.) of these materials.

This report does not deal in depth with the chemical composition of epoxy resins. However, a brief description of some of the important characteristics of epoxies is outlined in Appendix A. Also listed are numerous other references which detail physical performance characteristics and may be consulted for further information/1 to 71/.

1.2 Description of Materials

Epoxies used in construction are comprised of two liquid (or semi-liquid) components. The epoxide resin is the basic ingredient of the first component (commonly referred to as Part A or the base), and the hardening agent is the second component (commonly referred to as Part B or the curing agent). When the two components are mixed together, they react chemically (or cure) to form a solid mass. In addition, other materials, such as reactive flexibilizers, pigments, thickening agents, defoaming agents, coal tar, finely ground silica, or other secondary resins, may be incorporated into either component to achieve a wide variety of physical characteristics. Reactive diluents may also be added to reduce the viscosity. By selecting from a variety of epoxy resins, and an even greater variety of curing agents, virtually an infinite number of products can be formulated to meet the requirements of any specific application.

1.3 General Advantages and Disadvantages

Epoxies possess certain properties desirable in construction work, including: (1) good adhesion to most materials used in construction; (2) minimal shrinkage during curing and dimensional stability once hardened; (3) good chemical resistance to most acids, alkalies, salts, and solvents; (4) high compressive, tensile and flexural strength[1] - generally of the same magnitude as or greater than that of concrete; (5) excellent wear resistance; (6) ability to adhere to damp concrete surfaces (some epoxies); (7) good durability; and (8) good vapour barrier characteristics.

There are also some attendant disadvantages in using epoxies, such as: (1) critical requirement of proper surface preparation to attain desired bond - the bond attained will be greatly affected by the condition of the surface; (2) use limited to a specific temperature range; (3) generally short working life or period of practical use after the two components are mixed; (4) sensitivity of some epoxies to water; (5) difficulty of bonding epoxies to some materials, such as polyethylene and greased or waxed surfaces; (6) exact proportioning and thorough mixing requirement to ensure effectiveness; (7) limited thickness of placement due to high exothermic reaction; (8) high thermal coefficient of expansion compared with concrete[2]; (9) potential allergic reaction of workers; and (10) yellowing with age and exposure.

1.4 Typical Uses

Epoxies can be used to protect or repair concrete structures such as containment structures and irradiated fuel storage bays in nuclear power plants, chimneys, hydraulic structures, bridge decks, etc. They can be used for bonding, coating, sealing, grouting, or providing corrosion protection. Much of the confusion surrounding the use of epoxies stems from the fact that several different formulations can often accomplish the same task. While this is true in some instances, epoxies cannot be indiscriminately used to perform every function, as some types of epoxy systems are intended to perform properly, only under a given set of environmental and/or physical conditions.

In general, and for the purposes of this report, the use of epoxies will be discussed under five broad categories, each requiring different resin formulations and/or field procedures. These categories are:

1. Bonding plastic concrete to hardened concrete.
2. Bonding hardened concrete to hardened concrete or to metals.
3. Patching and filling voids, popouts, etc., in concrete pavements or structures.
4. Sealing cracks and joints.
5. Providing a protective coating.

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[1]Some epoxies, however, are designed to be flexible; therefore, the values of these strength characteristics will be reduced somewhat.

[2]Thermal coefficient of expansion can be lowered, closer to that of concrete, by incorporating a filler material.

2.0 GENERAL PROPERTIES OF EPOXIES

2.1 Mix Ratios

The mix ratios of epoxies must not be altered under any circumstances. The curing agents are an integral part of an epoxy formulation, designed so that a given amount of Part A will completely react with a given amount of Part B.

2.2 Fillers

Proper selection of fillers has a major influence on the handling characteristics, abrasion resistance and chemical resistance of an epoxy. This factor is second in importance to the resin binder (ie, Part A) selection. The proper blend of aggregate is vital if, for example, you are formulating an epoxy grout as a topping, bearing pad, patching material, anchor grout, etc. Note that, if only one size of aggregate is used with an epoxy, it will significantly restrict the workability of the system and the total amount of filler that can be used.

Specifically, fillers are also added to an epoxy to: (1) control the heat of reaction and reduce curing shrinkage; (2) improve abrasion and slip resistance; (3) increase the viscosity of the system for special applications, such as on vertical or overhead surfaces, and (4) alter the coefficient of thermal expansion. Unfilled epoxies can have a coefficient of thermal expansion in excess of 90×10^{-6} mm/mm/°C. The coefficient of thermal expansion for concrete is approximately 6 to 8×10^{-6} mm/mm/°C. The coefficients for filled epoxies can range from 12×10^{-6} to 32×10^{-6} mm/mm/°C, with the epoxy coefficient essentially being inversely proportional to the amount of filler used. The greater the amount of filler, the lower the thermal coefficient becomes, and it approaches 12×10^{-6} mm/mm/°C for the most highly-filled systems.

The difference between the coefficients of thermal expansion of epoxy and concrete is not as important in bonding or other applications where the bond layer thickness is approximately 3.2 mm (1/8 in) or less. However, when epoxy thickness is greater than 3.2 mm (1/8 in), as in patching, filling or topping operations, the difference in coefficients can be critical. Failure at the interface or in the concrete will result under conditions of freeze-thaw or heavy vibration, unless a low-modulus epoxy[3], or a highly-filled epoxy, is used.

2.3 Shelf Life

Most epoxies have a specified shelf life that is usually not more than a year. During storage, some ingredients in the base resin and hardener will separate and settle to the bottom. Thus, it is good practice to premix the components of each container (using different mixers for each container) to redisperse any material that may have settled, regardless of how long the container has been stored. If the material has crystallized (ie, coarse granular texture), it should not be used.

The ideal storage temperature for epoxies is 20°C. The epoxy should not be allowed to freeze, as this will also cause crystallization, and the maximum temperature during storage should not exceed 30°C for prolonged durations of time.

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[3]The modulus of elasticity of epoxy may increase significantly as the temperature decreases.

2.4 Temperature Sensitivity

To properly cure an epoxy and develop the maximum physical characteristics, a minimum temperature of 10°C is generally required[4]. This limitation is critical in that, if the temperature is below the minimum specified, the epoxy will not cure properly, or will cure at an extremely slow rate. Also, the viscosity increase may render some epoxies unworkable in the cold. Therefore, an epoxy should never be used if either the air or concrete substrate temperature is below the specified minimum for that product.

The higher the temperature, the more rapidly the epoxy will cure. If the temperature is too high, application difficulties will arise because the epoxy will set too rapidly. Generally, no maximum temperatures for use are given; however, temperatures are usually controlled by the worker's ability to apply the epoxy before the working life is spent.

2.5 Period of Practical Use

Once the epoxy resin and the hardener are mixed, a period of practical use (PPU), often referred to as the pot life, precedes initial set. In general industrial use, the term pot life is often interchangeable with PPU. However, each has a distinct meaning:

1. **PPU** refers to the actual time available under field conditions for proper and convenient application of the epoxy.
2. **Pot life** refers to the period of time between mixing the two components of the epoxy and when it gels. A material's pot life is determined under specific laboratory conditions to check its formulation for compliance with a given specification.

The length of the PPU depends on many factors, including:

1. Type of curing agent in the epoxy system. The agent is designed to cure the system over a specific temperature range.
2. Ambient and substrate surface temperature. The higher the temperature, the shorter the PPU, and conversely, the lower the temperature, the longer the PPU. At low temperatures, the viscosity increase may render some epoxies unworkable.
3. Temperature of resin and hardener at the time of mixing.
4. Volume of resin and hardener mixed.

If the mixed quantity of epoxy is small (eg, 250 mL), the heat generated is readily released to the atmosphere through the walls of the container. If the mixed quantity is large (eg, 2 L), the epoxy will react fairly quickly, harden within a short period of time (10-30 min) and develop high exotherms. If the epoxy is spread out in a thin layer (0.25 mm thickness) on a concrete surface, it will readily lose the heat generated by the reaction and will take longer to harden (ie, 2 to 5 h), depending on air and concrete temperatures.

2.6 Curing

Although most epoxies reach the end of their PPU and achieve initial set quite quickly, some may take several days to achieve full strength. Since temperature affects the curing time in much the same manner as it does the working life, additional time must be allowed for final curing in cooler weather. A minimum temperature of 10°C is generally required, although this will vary depending on the epoxy's formulation. In many instances, epoxy can be placed in service before final curing is attained, in much the same way as concrete, although a

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[4]Some epoxy formulations will cure at temperatures as low as 0°C and possibly even lower.

minimum strength level that will withstand the anticipated loading is required prior to exposure to service conditions.

2.7 Moisture

Most epoxies are sensitive to water or moisture. The presence of water in an epoxy formulation may severely affect the reaction and the properties of the cured system, and in some cases, water or moisture can completely prevent curing. Some specifications call for epoxies that are relatively insensitive to water. However, even with these systems, the amount of water present should be kept to a minimum, and water should never be mixed with an epoxy.

2.8 Shrinkage

Epoxies shrink very little during curing (approximately 3% for neat epoxies), and the shrinkage is less than that of concrete. Placement of epoxy in layers 3.2 mm (1/8 in) or thicker, on concrete that has been cured for less than 30 days, could result in excessive stresses in the concrete, the epoxy, or at the interface. These stresses may be large enough to cause bond failure at the interface. Therefore, placement of epoxy overlays or other thick-layer applications should be delayed until the concrete has sufficiently cured, ensuring that its future shrinkage will be minimal.

2.9 Durability - Chemical Resistance - Abrasion Resistance

The durability of hardened epoxy is excellent; however, it may yellow or chalk from exposure to weather.

Cured epoxies are generally quite resistant to chemical attack. Special epoxy systems are available to protect concrete surfaces from severe environments. Epoxies may also be used as moisture or vapour barriers; however, the conditions of use must be well understood.

Abrasion resistance of many epoxies is superior to that of concrete, and as in the case of chemical resistance, special formulations are available to handle the more severe exposures.

3.0 SURFACE PREPARATION

3.1 General

Successful application of epoxies depends directly on the condition of the surface to which they are applied. Surface preparation has a twofold purpose. The first is to remove any loose materials and any chemically bonded contaminants (eg, calcium hydroxide) from the surface of the substrate, which cover active adhesion sites. The second purpose is to increase the surface area by increasing the roughness and anchor patterns of the surface. By increasing the effective surface area, additional adhesion of the repair material to the substrate will result.

Concrete surfaces must be free of dust, oil, grease, laitance, curing compounds, form oil, or other surface contaminants. All surfaces must be clean and dry. A simple test for contaminated surfaces is to sprinkle water onto the surface, and if water beads form, it is an indication of contaminated concrete. Another test to determine whether excessive moisture is present on the surface, or when there is reason to suspect a condition of capillary moisture or hydrostatic pressure, is to place a rubber mat, about 600 x 900 mm, that is held in place by a suitable weight, on the test surface for 8 to 12 hours. If moisture collects under the mat during this period, the condition should be carefully assessed. The presence of moisture at the concrete-epoxy interface could result in failure of the application, because the epoxy will form a vapour barrier. Finally, it is advisable to run adhesion tests (eg, lift-off test) to determine the effectiveness of the cleaning efforts prior to the application of the topping. All surface preparation should be completed before any epoxy is mixed.

In addition to the necessity of proper surface preparation, good performance cannot be obtained when there is a poor or weak substrate. While contaminated surfaces can generally be determined by visual observation, visual inspection to determine the soundness of a concrete surface is often misleading. Experienced personnel can evaluate relative concrete strength by sounding with a hammer. For example, chipping of the concrete that results in fracture of the coarse aggregate is good indication of sound concrete.

Enforcement of specifications and proper inspection is essential to provide the contractor with a clear understanding of the necessity for proper surface preparation.

3.2 Removal of Unsound Concrete

The first step in this procedure is that the periphery of the area, from which the concrete is to be removed, should be deliniated by cutting the concrete. These cuts should actually be made several inches outside the limits of the defective concrete area, and the cuts should be of a minimum depth so as to ensure adequate adhesion of the repair material. When using an epoxy-bonded Portland cement concrete, a recommended minimum depth of repair (and hence cut) is 40 mm (1-1/2 in), and for an epoxy mortar a recommended minimum depth of repair is 13 mm (1/2 in). However, these are minimum depths only, and all deteriorated or damaged concrete should be removed until sound material is reached. These peripheral cuts can be made using a diamond saw and/or pneumatic tools. Use of a diamond saw is preferred as it reduces the chances of edge spalling or other weakness that might be produced by other methods, and it also produces a shoulder against which the epoxy can be placed and smoothed (ie, no feather edging).

Once the cuts have been made, the concrete may be removed using well controlled mechanical methods, such as chipping hammers, water blasting, sand blasting, etc. On large horizontal areas, mechanical scarifying machines may be economically used. If these machines are used, it is important to subsequently sand blast the area to remove fractured or weakened concrete. Note that the surfaces to be repaired should be roughened, but kept as uniform as possible.

3.3 Preparation of Concrete Surfaces

New concrete surfaces or other surfaces freshly exposed due to concrete removal (see Subsection 3.2) must be cleaned before an epoxy is applied. The cleaning must remove any laitance, curing membranes, paint, oil, grease, silicones, dust, dirt, asphalt, mortar, or any other surface contaminant or defect. Sandblasting is the preferred method to clean concrete before epoxy application. If that is impractical, light chipping, mechanical scarification or other mechanical abrading of the surface may be used. After sandblasting or abrading, any remaining dust or other debris must be cleaned by oil free high-pressure air or water jets.

3.4 Preparation of Metal Surfaces

Steel and other metal surfaces must be free from dust, dirt, oil, grease, rust, mill scale, weld splatter, or other contaminants. Oil and grease may be removed with mineral spirits, high boiling naphtha, xylol, or other non-chlorinated solvents. These chemicals should be used only in areas with good ventilation. Rust, mill scale, etc., can be removed by sandblasting or other mechanical abrading methods. Blasting or abrading also roughens the surface and improves the anchor patterns of the steel, resulting in an improved epoxy bond. Do not sandblast or abrade galvanized metals. All these methods should be followed by an oil free air blasting to remove dust and debris. Note that steel thus cleaned is highly susceptible to corrosion and, therefore, should be coated as soon as possible. Some metals (eg, galvanized) may require special treatment before bonding. In such cases, the epoxy manufacturer should be contacted for guidance on proper surface preparation requirements before any attempts at bonding is made.

4.0 EPOXY PREPARATION

4.1 Temperature Conditioning

Epoxy components should be conditioned at a proper application temperature (usually 18° to 24°C) before use. Viscosities of the components are directly related to temperature. At lower temperatures, viscosity will be higher and could cause difficulty in mixing and application. At higher temperatures, the viscosity will be lower, thus allowing easier mixing, but the reaction rate will be increased, shortening the time available for application. Best results will be obtained when the temperature of the components at the time of mixing is within the specified range. Some manufacturers offer different temperature grades (ie, refer to ASTM C 881). In these instances, each epoxy will be formulated to give the same pot life and cure rate when mixed and applied within a specified temperature range.

4.2 Mixing Epoxy Components

Epoxy components should be mechanically mixed at low speeds to prevent entrapment of air. A mechanical mixer attached to a 13 mm (1/2 in) electric drill is often used, because it produces complete mixing quicker than by hand mixing, which in turn will allow more time for application. For larger batches, a mortar mixer is recommended. In all cases, the resin and hardener should be mixed for at least 3 minutes. Aggregate and epoxy should be mixed until uniform. Whenever possible, the entire contents of the two component containers should be mixed at one time to ensure the proper mixing ratio. Where this cannot be done, the components should be carefully measured to maintain the proper proportioning. The sides and bottom of the containers should be scraped to remove all contents.

4.3 Aggregates for Epoxy Mortars

Normally, prepackaged aggregates are supplied with the epoxy. However, in situations where the user uses his own aggregates, the aggregates for producing epoxy mortars for patching purposes should meet the requirements specified by the manufacturers. Aggregates should have the proper particle size and grading to reduce its impact on workability. The aggregates must be clean, dry, and conditioned to a temperature within the temperature range of the epoxy to be used. Aggregate should be added slowly during mixing and mixed until a uniform blend is obtained. If no ratio is specified for an epoxy, in general, up to four parts by volume (ie, Part A and B) of Ottawa silica sand, or up to three parts by volume of other fine aggregate can be added. Adding aggregate to an epoxy will tend to increase the mixture's PPU; however, workability reduces as the amount of aggregate increases.

5.0 APPLICATION PROCEDURE

5.1 General

The placing procedure consists of five sequential steps that are generally common to all applications: (1) preparation of the substrate to be bonded; (2) temperature conditioning of the epoxy components, aggregate (if used), and substrates; (3) mixing of epoxy; (4) application of the epoxy mortar to the substrate; and (5) forming, consolidating, and finishing of the epoxy mortar. The last step is mostly applicable when patching spalls and filling voids.

Each step must be well planned before starting, so that work may progress without delay. All materials, tools, and equipment must be available at the time and place where they will be used. Time, temperature, and surface conditions are more critical when working with epoxies than with other construction materials. Delays cannot be tolerated, as there is much less margin for error. When epoxy placement is done in the open, it must be stopped in the event of rain, and not resume until after the surfaces are dry again. Rain on an epoxy surface that is dry to the touch is not likely to have an adverse effect, but should be avoided when possible. All placed, uncured epoxy must be protected from rain.

Once the surface to which the epoxy is to be applied has been cleaned, dried, and rendered sound, care must be taken to ensure complete coverage (ie, wetting of the substrate to be bonded). High-viscosity systems will often need to be scrubbed into the surface to ensure complete wetting. When using high viscosity epoxy resins or epoxy mortars, a neat (no-aggregate) wetting coat of epoxy may be needed. This prime coat may be applied in a relatively thin single coat, with the high viscosity resin or the epoxy mortar being placed while the prime coat is still tacky.

Additional issues relating to the proper application of epoxies are as follows.

5.2 Rate of Application

The rate of application, or the thickness obtained per coat, depends on the viscosity of the formulation, temperature of both the epoxy and the surface to be treated, and surface texture. For most bonding applications, a 0.25 to 0.4 mm (0.010 to 0.016 in) thickness is desirable. When multiple coats are to be applied in a bonding application, it is recommended that the manufacturers' instructions be closely followed when determining optimum curing times (at various temperatures) for the first coat. Generally, a minimum period of 16 hours at 23°C and 24 hours at 10°C is sufficient curing before the second coat is applied. If a solvent based material is being applied, it must be well cured prior to placing the top coating.

5.3 Controlling the Hardening Rate

The most important factors in controlling the rate of hardening are: (1) the type of epoxy compound chosen, (2) the substrate temperature, (3) the ambient temperature, and (4) the maximum temperature of the mixed epoxy due to the exothermic reaction.

When the substrate surface and air temperatures are near or below the specified minimums, it will be necessary to preheat the epoxy and substrate surface to acceptable temperatures. This can be accomplished by infrared heaters or by providing an enclosure heated by circulating warm air. In either case, uniform heating is required. Direct flame heating must never be used. The substrate temperature should be maintained at 10°C or greater, until the epoxy has cured.

On warm days, it may be desirable to increase the working life (ie, PPU) of the epoxy to allow more time for the application. This can be done by using a slower reacting epoxy with a longer pot life. Also, the area being repaired can be protected from direct sunlight by a tarpaulin before, during, and after epoxy placement. The epoxy components, in their separate containers, can also be stored at a low temperature before mixing, and once mixed, the epoxy can be spread into a thin film on a clean temporary surface. This latter procedure will help dissipate the heat generated by the reaction, thereby preventing the epoxy from setting in the mixing container. Care should be taken, however, to prevent cooling of the components to a point that they become too thick for proper mixing or application.

5.4 Bonding Plastic Concrete to Hardened Concrete

For this application (and in general), the bond line should be kept as thin as possible, but thick enough to ensure complete contact between the two concrete layers. A bond line thickness between 0.25 and 0.40 mm (0.010 to 0.016 in) thick is usually required. The epoxy may be applied by broom, brush, squeegee, roller, airless sprayer, or trowel, using sufficient force to ensure complete wetting of the hardened concrete surface. The hardened concrete surface should be prepared as previously described (see Section 3.0) and blown clean with dry oil free compressed air immediately before epoxy placement. If the base concrete is relatively flat and smooth, a low viscosity epoxy should be used. However, if the surface is irregular or rough, a higher viscosity epoxy should be used because it will not readily run off the high spots and will yield a more uniform thickness. Similarly, a higher viscosity epoxy should be used on vertical surfaces. Every effort should be made to achieve a more uniform surface so that the least amount of material is consumed.

Only epoxies that are relatively tolerant of moisture conditions should be used for this purpose, and as well, high-slump concrete should be avoided. If vibrators are used during the placement of the new concrete, it may be desirable to delay placement until the epoxy has become tacky, because vibration may emulsify the epoxy film and remove it from the surface. However, if concrete placement is delayed so that the epoxy is no longer tacky, it is necessary to apply a second coat. It should also be noted that some manufacturers recommend the placement of fresh concrete while the epoxy bonding agent is still fluid.

When needed, forms should be placed after all surface preparation has been completed. Any debris resulting from the forming operation must also be removed. Forms should be lined with a polyethylene sheet or other release agent, to prevent adhesion to the epoxy material.

5.5 Bonding Hardened Concrete to Hardened Concrete or to Metals

The bond line thickness for this application should also be kept as thin as possible, that is, the bond line should be no thicker than that needed to ensure complete contact between the two surfaces. If the substrates match (ie, fit relatively flush) and there are only small voids to fill, an unfilled or slightly filled epoxy should be used. If the substrates do not match, leaving large voids to be filled, or if the joint is to be subjected to excessive vibration, or if materials of different coefficients of thermal expansion are to be bonded, a highly filled epoxy should be used.

After the surfaces have been properly prepared, epoxy should be applied to both surfaces and worked to ensure complete wetting. If the surfaces are absorptive, a second coat may be applied while the first coat is tacky and just immediately before joining the surfaces together. The surfaces should then be firmly placed together and clamped (if possible) for a minimum of 24 hours at 23°C, or for a longer period under a colder temperature (ie, 10°C). Provision should also be made to prevent epoxy from leaking at the joints.

5.6 Patching Spalls and Filling Voids

Epoxy mortars, consisting of epoxy and sand or other fine aggregate, are suitable for patching spalls and filling voids and popouts as deep as 75 mm (3 in). The void should first be coated with a neat epoxy before applying the mortar. In warm weather, it may be necessary to fill a void in several lifts, to dissipate the heat generated. The material should be allowed to cool down before applying the next lift. Depending on the length of time between successive lifts, it may be necessary to re-prime the surface with epoxy before placing the next lift. Also, note that patches should never be applied over existing joints, and if a patch will be subjected to severe

freeze/thaw cycling, a more flexible[5] or a highly filled epoxy can be used. Voids deeper than 75 mm (3 in) are generally filled with Portland cement concrete. However, epoxy can be used to enhance the adhesion between the hardened and plastic concrete, as was discussed in Subsection 5.4.

The placed epoxy mortar may be consolidated and finished by methods similar to those used for Portland cement concrete mixes. Care should be taken to trowel the mortar onto the sides and into the corners of the void. Due to the relatively short working life, consolidation and finishing must be performed without delay. In final finishing, care should be exercised to avoid splashing and spillage of epoxy onto the surrounding concrete surfaces, as its removal could be difficult, once hardened.

Epoxy will build up on the finishing tools, requiring frequent solvent cleaning. Excess solvent must be wiped from tools with a clean rag before continuing. Care should be taken to obtain the desired surface texture for the intended application. If a smooth, dense finish is required, the trowel should be kept slightly moistened with mineral spirits.

5.7 Sealing Cracks and Joints

Cracks in concrete, as small as 0.08 mm (0.003 in) wide, can be repaired by injecting with a low viscosity epoxy. The first step in successful crack repair, however, is to determine the cause of the crack. Further, if the crack affects the structural integrity of the member, an investigation should also be undertaken to evaluate the appropriateness of sealing the crack with epoxy.

If epoxy injection is chosen, the interior of the crack should first be properly prepared before applying the surface seal and injection ports, as the concrete can be restored to its original condition only if the crack is not contaminated. If possible, dust and debris should be removed from the crack using an air jet or water jet. Low-viscosity epoxy can be injected using a pressure pot, caulking gun or a positive displacement injection machine. Injection should start at the "bottom-most" or "end-most" port and proceed upward or across until the crack is completely filled. After the epoxy has cured, the injection ports and the surface seal may be removed, if required.

5.8 Protective Coatings

Epoxies are used for protective coatings as they will protect the concrete from attack by chemicals and salts and from ingress of water (ie, vapour barrier). This water vapour barrier property is beneficial in keeping water from penetrating into the concrete substrate, thus making the concrete less susceptible to freezing and thawing or wetting and drying damage. Conversely, an epoxy vapour barrier can be a detriment, if it prevents water vapour from leaving the substrate. When this occurs, freezing conditions can result in the formation of ice which may disrupt the coating. Disruption of the coating will also occur if vapour pressures are high enough.

Regardless of the protective coating to be applied, the surface preparation practices used for bonding applications, as well as the manufacturer's instructions, must be followed. Application should follow the specified rates and may be accomplished by brush, broom, squeegee, roller, or trowel. When applying a protective coating, sufficient force should be used to ensure complete wetting of the concrete. In addition to being a protective coating, an epoxy can be spread on a horizontal surface and fine aggregate broadcast on the uncured epoxy to create a non-skid surface.

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[5] Unless properly formulated, a flexible (ie, low modulus) epoxy will tend to lose its low modulus properties at low temperatures.

Some epoxies are subjected to an amine blush, which is a greasy film that appears on the surface after curing. If a second coat is to be applied, this film must be removed by washing it with soap or detergent and water or a solvent wipe. Following cleaning, the surface should be thoroughly rinsed with water and dried before proceeding.

6.0 CLEANING AND HANDLING PRECAUTIONS

Epoxy resins cannot be cleaned or removed using ordinary solvents after they have cured. Therefore, disposable equipment or tools that can be cleaned before the epoxy cures should be used. Mixing containers of polyethylene are recommended because epoxy will not adhere to these materials. Cleaning equipment before the epoxy hardens can be accomplished using methyl ethyl ketone, perchloroethylene, trichloroethane, or other solvents recommended by the manufacturer. Since many of these materials are flammable and/or toxic, they should be used only in well ventilated areas and with protective clothing. Equipment should be thoroughly dried before it is used again.

Some users may find that contact with epoxies causes skin irritation similar to poison ivy. Others may find that contact with the components causes skin sensitization that will ultimately result in an irritation. The face and hands should always be protected when handling epoxies. In addition to normal protective clothing, protective creams, rubber gloves, and face shields are available to protect the skin and eyes. In the event of skin contact with an epoxy compound or uncured mixture, the affected area should be washed immediately with soap and water. Solvents should not be used as they dilute the epoxy, and this will allow the epoxy to penetrate the skin more easily. Solvents will also dry out the skin, making the epoxy handler more sensitive to future contact. If contact with the eyes occurs, flush the eyes with large amounts of water, followed by immediate medical attention.

In summary, due to the possibility of burn, eye damage, etc., safe handling practices are essential. Guidance is available by consulting the Material Safety Data Sheets (MSDS's) that are required for various controlled products (ie, chemicals), as per WHMIS legislation. It is also recommended that Ontario Hydro's Health and Safety Division be contacted to verify the requirements for necessary protective equipment and precautions when using these materials. With proper safety and handling precautions, these materials can be safely used. Further details on the safe handling of epoxies are given in Appendix B.

7.0 COST

Cost is one of the factors limiting the use of epoxy. However, cost should be considered not only from the standpoint of initial price of the material, but also with regard to labour, time, and inconvenience. The ability to extend the epoxy resin system by the use of fillers will lessen the cost, although it should be cautioned that extending the resin too far will reduce the system's workability and adhesion.

8.0 ONTARIO HYDRO REPORTS

Over the past few years, a considerable amount of work has been carried out to investigate the use of epoxy systems for various concrete repair or construction projects. A large data base of information has been developed and is available in the following Research Division reports.

Report Number	Title
90-71-K	Lakeview TGS Chimney 3 - Assessment of Flexible Epoxy and Polyurethane Injection Resins for Use in Repairing Cracks

SSS-34-K	Lakeview TGS Unit 2 - Chimney 2: Assessment of Epoxy Injection Resins for Use in Repairing Cracks
87-261-H	Evaluation of Suitability of Existing Repair Materials (Phase II) - Laboratory Program
SS7-57-K	Evaluation of Epoxies for Underwater Repairs
SS7-9-K	Pickering NGS "A" Vacuum Building - Performance of Epoxy Injected Cracks in the Concrete Base Slab
SS6-33-H	Evaluation of ST435 and Everset Epoxy Bonding Agents
SS5-3-H	Pickering NGS "A" Vacuum Building Floor Slab - Evaluation of Epoxy Grouts
SS4-22-H	Evaluation of Talygrout 200 Epoxy Grout
83-518-H	Evaluation of the Sealing of Cracks in Concrete Containment Structures by Epoxy Injection
83-349-H	Field Evaluation of Epoxy Injection of Concrete Cracks, Vacuum Building, Pickering NGS "A"
82-343-H	Pickering NGS "B" - Sealing of Joints in the Spent Fuel Transfer Duct Between Unit 5 and 6
82-329-H	Field Evaluation of Epoxy Injection of Concrete Cracks, Vacuum Building, Pickering NGS "A"
82-146-H	Re-examination of Pickering NGS "A" Vacuum Building Floor Slab (Underside)
582-58-H	Review of Vacuum Building Floor Slab Cracks - Pickering NGS "A"
582-56-H	Pickering NGS "A" Vacuum Building Floor Slab - Progress Report of Repair Work
582-46-H	Effect of Temperature and Water on the Bond Strength Characteristics of Epoxy Grout
582-9-H	Repair of Vacuum Building Floor Slab - Concrete Cores: Preliminary Report
81-474-H	Epoxy Injection Resins for Concrete Crack Repair
581-66-H	Repair of Vacuum Building Floor Slab - Concrete Cores: Preliminary Report
81-32-H	Organic Load Bearing Grouts
Draft Procedure April, 1980	Procedure for Repairing of Concrete Structures by Epoxy Injection (Currently being revised and updated)
80-368-H	Evaluation of Epoxy Resins for Grouting Bruce NGS "A" Preheater Enclosures
80-345-H	Evaluation of Repaired Concrete - Vacuum Building Wall: Bruce GS "B"

S80-37-H	Evaluation of Devcon F-2 and Plastic Steel Epoxy Grouts
S79-13-H	Grouting of Preheaters at Bruce NGS "A"
S78-47-H	Length Change Measurements of Epoxy Grouts
S78-7-H	Evaluation of Anchor Grouting Materials for Winter Construction
77-313-H	Concrete Anchor Rod Pullout Tests: Bruce GS
C77-199-H	Organic Grouting Materials Review

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APPENDIX A

Important Characteristics of Epoxies

IMPORTANT CHARACTERISTICS OF EPOXIES

A.1 General

Epoxy resins have a remarkable combination of properties that make them attractive for use in concrete construction or repair. Some of these properties include:

Versatility in Formulation and Use	Various curing agents and modifiers are available, which can be mixed with the epoxy to vary its physical and chemical properties. Epoxies can be applied in a fluid state and, within a few hours, will cure under ambient conditions to either a rigid or semiflexible solid. The physical and/or strength properties of a hardened epoxy usually exceed those of the concrete. Epoxies can be applied in varying thicknesses, without affecting the physical and chemical properties.
Handling Characteristics	Most epoxy systems can be mixed at room temperature and will cure without additional heat.
Adhesive Properties	Epoxy resins provide high adhesive strengths and will bond to a variety of materials.
Low Shrinkage	Negligible shrinkage, usually less than three percent during curing for most formulations.
Inertness	Cured epoxy resin systems are chemically inert.
Durability	Good freeze/thaw and chemical resistance.
Application	Can be applied by spray guns, trowels, caulking guns, injection equipment, or other hand tools.

A.2 Summary of Advantages/Disadvantages

The final properties of epoxy-based adhesives will depend on the whole system, that is, the type of resin, the curing agent, fillers and modifiers (see Section A.5). Before deciding whether to use epoxies for a particular application, it is important to keep in mind the advantages and disadvantages or limitations.

Some of these advantages/disadvantages are outlined below:

Advantages	Disadvantages/Limitations
Good adhesion	Physical properties different from concrete
High compressive/tensile/ flexural strength	Adversely affected by improper proportioning and lack of mixing
Excellent freeze/thaw resistance	Can cause allergic reaction in workers
Good resistance to chemical attack	High exothermic reaction when used neat
Good wear resistance	Limited thickness
Impermeable	High coefficient of thermal expansion
Minimal shrinkage and dimensional stability	Physical characteristics are reduced at elevated temperature
Excellent radiation resistance	Higher creep than that of concrete
Some formulations are water compatible	Curing time dependent upon application temperature
Viscosity can be varied	Some systems can not be used in a moist environment

A.3 Applications

Five general categories of use for epoxy resins are:

1. Bonding fresh concrete to hardened concrete.
2. Bonding hardened concrete to hardened concrete or to metals.
3. Patching and filling voids, popouts, etc., in concrete pavements or structures.
4. Sealing cracks and joints.
5. Providing a protective coating.

A.4 Evaluation

Test conditions for epoxy resin materials are described in A.S.T.M. Standards and British Standards. These standard test conditions are appropriate for comparing the performance of one epoxy with another. However, the standard test conditions may well be misleading for actual service conditions, and therefore, materials may have to be tested under intended placement and service environments to ensure their adequacy. When using an epoxy resin as a repair material, it is important to define those properties that will allow a measure of the actual site performance.

A.5 Chemistry

The chemistry of the epoxy compounds is complex. Some important points which may assist the reader in appreciating these materials are briefly described below.

A.5.1 General

Liquid epoxy resins are comprised of epoxide groups that serve as reaction sites for polymerization. Curing agents contain functional groups, which react with the epoxide groups to form a crosslinked polymer. Curing agents are available in a large range of viscosities and pot life. The pot life can be varied from a few minutes to several hours.

The curing or process of hardening (polymerization) is initiated by the chemically active reagent known as the curing agent, hardener, activator, or catalyst. Some curing agents promote hardening by catalytic action, while others participate directly in the reaction and are absorbed into the resin chain. Depending on the type of curing agent, hardening is accomplished at room temperature, with heat produced by exothermic reaction or may require external application of heat. In general, the higher the reaction temperature, the faster the hardening process is completed (ie, pot life is shorter). When large volumes of epoxy resin are batched, the curing reaction is much faster in the mass due to the release of a large amount of heat, and also due to the slow release of heat from the bulk.

The thermoset product that results from the reaction of the resin and hardener is unlike that of typical thermoplastics in that it does not melt or flow when heated, but becomes more rubbery and gradually loses strength with an increase in temperature. Since the reaction does not involve condensation polymerization and no low molecular weight substances, such as water split off during the reaction, shrinkage is minimal. As a result, epoxy resins are valuable adhesives. The optimum properties of an epoxy are realized by careful attention to the chemistry of both the resin and the hardener.

The combination of aliphatic, aromatic ether and hydroxyl groups in the original epoxy resins, plus the amine, ester and other groups formed by reaction with the curing agent, all provide a range of structures, polarities and hydrogen bonding, which is compatible with, and attracted to, a wide variety of surfaces. This produces good wetting and penetration, which is particularly important in adhesives. The high degree of cross-linking in the cured structure produces hardness, strength, heat resistance, electrical resistance and broad chemical resistance. These properties are important in coatings and adhesives.

The bisphenol-A epoxy-based adhesive is probably the most versatile of all high strength adhesives. A number of factors determine the properties of a cured resin. These factors include the properties of the epoxide and the hardener, the nature of functional groups of the hardener, the overall structure of both the epoxy resin and the hardener, the ratio of hardener to resin, and the temperature of curing. Further modifications can be made with diluents, extenders, flexibilizers, fillers and pigments. Some of these additions may produce desired properties in the freshly mixed and hardened material (ie, increased viscosity in the plastic state and improved flexibility in the hardened state).

However, to achieve the optimum in a given property may mean downgrading another; hence, the required amount of hardener, modifier, diluent, filler, etc., depends on what is required of the cured material. These components are now discussed.

A.5.2 Curing Agents

The type of curing agents used with thermosetting resins is very important as they determine the final mechanical, thermal and chemical properties, by influencing the balance between pot life and rate and extent of cure. A large number of curing agents will only react at high temperatures and, therefore, are not suitable for general use. Two of the basic types of curing agents used in epoxy resin compounds are amines and acid anhydrides. Amine curing agents are the most widely used. The resultant mixtures have low viscosity, are either rapid or slow curing at normal temperatures, are relatively tough, and are either hygroscopic or non- hygroscopic. The non-hygroscopic are useful with plastic concrete. Acid anhydrides require high temperatures for curing and

have high resistance to heat and chemicals, but are hygroscopic. The properties of the cured system are dependent not only upon the curing agent selected, but also on the amount of curing agent used.

Whether the curing agent is a catalyst or reactive hardener, hardening action starts as soon as the curing agent and resin are mixed together, resulting in the evolution of heat. When large amounts of epoxy resins are used in thick sections, the high temperature developed will result in a faster rate of cure. In adhesive bonding, the bond (glue) line is ordinarily thin, and the heat developed by the curing reactions is largely conducted away. Consequently, hardeners with the fastest rate of cure are preferred when no external heat is supplied to the adhesive. With commercially available hardeners, the recommendation of the resin manufacturer should be followed to optimize the particular physical characteristics inherent in the system.

To overcome the brittle characteristics of cured epoxy resins, certain hardeners have the ability to give the resin flexibility and toughness. By choosing an inhibited hardener, full curing can be avoided, and thus the resin will remain flexible.

A.5.3 Resinous Modifiers

Resinous modifiers are sometimes added to the system as fillers. Generally, they are added to impart flexibility, high impact strength, greater thermal shock resistance, and a greater resistance to deflection at higher temperatures (ie, greater heat deflection temperature) to the system. Modifiers include polysulphides, polyamides and aliphatic amines. Plasticizers, which are inert resinous fillers, and flexibilizers form more elastic materials. Incorporation of flexibilizers into epoxy resins generally increases the mobility of the epoxy molecules and has the expected softening effect upon mechanical properties. Flexibilizers generally decrease modulus, hardness, stiffness, glass transition temperature and produce materials of increased flexibility.

A.5.4 Diluents

Reactive diluents are added to control the viscosity of the resin to meet particular application conditions. They are used primarily to reduce the viscosity of the mixed system, although they can provide modification of the cured properties. They also alter the wetting ability of the formulation and generally increase the loading volume of fillers. A reactive diluent is a low-viscosity liquid that is capable of combining chemically with the resin-hardener system. The extent to which the properties of a cured system are reduced is a function of the concentration of diluent, with the larger amounts being used for viscosity reduction and lower amounts to retain certain properties of the cured system. Diluents can also be used to modify the pot life. Many reactive diluents are glycidyl ethers (allyl and butyl glycidyl ether), octylene oxide and styrene oxide. Diluents, in general, lower the physical properties (eg, chemical resistance) of the cured resin system.

A.5.5 Fillers

Fillers which are normally inert can be either organic, inorganic, metallic or nonmetallic and are added to the resin system to reduce cost and generally improve certain physical characteristics. Some of the advantages and disadvantages of using fillers are noted below:

Advantages

- Reduces exotherm
- Reduces shrinkage
- Increases compressive strength and modulus
- Increases surface hardness
- Increases thermal conductivity
- Reduces thermal coefficient of expansion
- Improves thermal shock resistance

Disadvantages

- Reduces tensile strength
- Reduces flexural strength
- Reduces workability

- Increases adhesive strength by decreasing shrinkage
- Increases specific gravity of the cured systems
- Increases pot life

A word of caution is that some fillers can either adversely or advantageously affect certain properties (eg, moisture resistance, vapour transmission and solvent resistance) of the cured system, depending on the specific resin/filler combination and proportions thereof.

Although the majority of fillers used in epoxy are finely divided, coarser materials (ie, sand, gravel, etc.) are also used. Fillers tend to settle from the resin and the amount of settling is dependent on the specific gravity of the filler, particle size of the filler, resin used, and viscosity of the mixed material. It is generally necessary to provide some finely divided filler when coarse fillers are incorporated into the mix to reduce settling. Where viscosity of the epoxy decreases during the reaction (ie, resulting from high-temperature cures), this often increases the settling tendency and results in stratification of the filler upon gelation.

Fillers alter the physical state of the uncured resin and in some cases produce partial thixotropy. Materials used for this purpose include glass fiber, silica bentonite, aerosil, cabosil, and mica platelets. When these particular fillers are added in larger proportions than normal fillers, they can impart a putty-like consistency. Generally, particulate fillers cause the least increase in viscosity, while fibrous fillers increase viscosity the most. Regardless, where epoxies with pourable viscosities are desired, the amount of filler is restricted. Often fillers are added to increase impact strength. A less obvious effect of fillers is that of reducing permeability.

Inert solids such as sand or calcium carbonate (ie, aggregates) and metals are also used to reduce resin content, thermal shrinkage and coefficient of thermal expansion. Where fillers are incorporated, the workability of epoxy reduces, and care should be taken to prevent having a starved bond (glue) line at the epoxy-substrate interface.

Where fillers are incorporated into the resin, they should be dry to obtain optimum results. Also, an effort should be made to reduce air entrapment during mixing.

A.5.6 Pigments and Dyes

Pigments and dyes, which can be organic or inorganic, can be used as fillers where colour matching is desirable; however, not all hardeners are colour stable, and the resin may tend to darken with time.

APPENDIX B

Suggested Industrial Hygiene Practices For Handling Epoxy Resins

SUGGESTED INDUSTRIAL HYGIENE PRACTICES IN HANDLING EPOXY RESINS

1. Education

Supervisors and workers should know about the possible harmful effects on skin in handling these materials. All unnecessary skin contact with these materials should be avoided.

2. Personal Hygiene

Good personal cleanliness is important.

1. Personnel should be instructed to avoid skin contact with resins, hardeners, solvents, or mixtures.

2. Adequate washing facilities close to the work area should be provided. This includes wash basins, with hot and cold water, clean towels and skin creams.

3. Where indicated, the provision of showers should be considered.

4. Time should be provided for washing before eating, smoking, and rest periods.

3. Protective Equipment

Equipment to minimize personal contact should be provided.

1. Gloves should be worn wherever the possibility of skin contact exists. Contaminated gloves should be cleaned regularly, preferably by washing in soap and water.

2. Gauntlets and Sleeves should be worn where indicated.

3. Coveralls with sleeves should be provided daily, where there is repeated or prolonged work with these materials. Contaminated clothing should be removed promptly and laundered before re-use.

4. Aprons may be necessary for certain operations.

5. Full Face Shields should be worn wherever there is a possibility of droplet contamination.

6. Protective Creams may be used as a supplement to protective clothing.

7. Skin Lotions or Creams may be used routinely after washing to maintain the skin in good condition.

4. Handling Procedures

Mixing and application techniques should be devised to minimize skin and vapour contact. The techniques should address the following requirements:

1. Mixing of resin, curing agents and other ingredients should be done in areas with satisfactory local ventilation. A laboratory-type booth with a face velocity of 0.5 to 0.8 m/s (100 to 150 f/s) would be suitable.

2. Curing operations should be done in areas with exhaust ventilation.

3. Heat curing operations should have local exhaust.

4. Grinding and finishing operations of the cured resin should be locally exhausted.

5. Housekeeping in the work area is important. Contamination of work places is to be avoided. Disposable paper may be used on bench tops and the floor.

5. First Aid Measures

1. Accidental splashes of any of the ingredients, particularly the hardener, in the eye should be washed immediately with copious amounts of clean water. This should be continued for 15 minutes, and a physician should be consulted.

2. Accidental skin splashes should be cleaned thoroughly with soap and water. The use of solvents on the skin should be avoided. Clothing wet with resin, hardener or solvent should be removed and the skin washed with soap and water.

3. Workers developing skin trouble should be removed from further exposure and treated promptly. Generally, such workers can return in a short time.

6. Fire Control Measures

The solvents used are flammable and should be stored and handled with care. Solvent should be handled in safety cans in the work area.

The resins and hardeners will burn, but are not considered acute fire hazards.

7. Health and Safety Division

It is recommended that Ontario Hydro's Health and Safety Division be contacted to verify the necessary protective equipment and precautions when using these materials.